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Chemical Abundances and the Metagalactic Radiation Field at High Redshift

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ABSTRACT

We have carried out a series of model calculations of the photoionized intergalactic medium (IGM) to determine the effects on the predicted ionic column densities due to uncertainties in the published dielectronic recombination (DR) rate coefficients. Based on our previous experimental work and a comparison of published theoretical DR rates, we estimate there is in general a factor of 2 uncertainty in existing DR rates used for modeling the IGM. We demonstrate that this uncertainty results in factors of ~ 1.9 uncertainty in the predicted N V and Si IV column densities, ~ 1.6 for O VI, and ~ 1.7 for C IV. We show that these systematic uncertainties translate into a systematic uncertainty of up to a factor of ~ 3.1 in the Si/C abundance ratio inferred from observations. The inferred IGM abundance ratio could thus be less than $(\mathrm{Si/C})_\odot$ or greater than $3(\mathrm{Si/C})_\odot$. If the latter is true, then it suggests the metagalactic radiation field is not due purely to active galactic nuclei, but includes a significant stellar component. Lastly, column density ratios of Si IV to C IV versus C II to C IV are often used to constrain the decrement in the metagalactic radiation field at the He II absorption edge. We show that the variation in the predicted Si IV to C IV ratio due to a factor of 2 uncertainty in the DR rates is almost as large as that due to a factor of 10 change in the decrement. Laboratory measurements of the relevant DR resonance strengths and energies are the only unambiguous method to remove the effects of these atomic physics uncertainties from models of the IGM.

Subject headings: atomic processes – cosmology: miscellaneous – diffuse radiation – intergalactic medium – quasar absorption lines

1. Introduction

Many fundamental question of cosmology can be addressed through observations of the Ly-α forest. For example, observation of metal absorption lines can be used to constrain the spectral shape and history of the metagalactic radiation field, the chemical evolution of the universe, and the initial mass function (IMF) of the earliest generation of stars (Songaila & Cowie 1996;

Giroux & Shull 1997; Boksenberg 1998; Songaila 1998). Interpreting spectra from the Lyα forest is carried out using both single phase models (Giroux & Shull 1997; Songaila 1998) and cosmological models of the IGM employing semi-analytic approximations or hydrodynamical simulations (Miralda-Escudé et al. 1996; Bi & Davidsen 1997; Hellsten et al. 1997; Rauch, Haehnelt, & Steinmetz 1997; Zhang et al. 1997; Gnedin & Hui 1998; Riediger, Petitjean & Mückert 1998; Madau, Haardt, & Rees 1999). These various models use different approximations and assumptions. However, one thing they all have in common is the need to calculate the ionization structure of the photoionized IGM. This is typically carried out using plasma codes which are written specifically for modeling the ionization structure of photoionized gas. One of the most commonly used codes for this purpose is CLOUDY (Ferland et al. 1998).

Fundamental to the accuracy of these plasma codes and any inferred astrophysical conclusions is calculating the correct ionization balance. This in turn depends on the accuracy of the dielectronic recombination (DR) rates at IGM temperatures ($\sim 10^4$ K). At these temperatures DR is the most important electron-ion recombination process for almost all ions (Arnaud & Rothenflug 1985; Arnaud & Raymond 1992; Kallman et al. 1996).

In this Letter we demonstrate that uncertainties in the DR rates for C IV, N V, O VI, and Si IV signficantly hamper our ability to constrain reliably the chemical abundances and the shape of the metagalactic radiation field at high redshift. In Sec. 2 we review the status of the relevant DR rates and their uncertainties. The model we use to calculate the ionization structure of the IGM is presented in Sec. 3. In Sec. 4 we present the results of our simulations, demonstrate the effects of the estimated uncertainties in the DR rates, and discuss the astrophysical implications. We present our conclusions in Sec. 5.

2. Dielectronic Recombination

The lack of reliable DR rates is the dominant uncertainty in ionization balance calculations of photoionized plasmas (Ferland et al. 1998). A critical evaluation of published theoretical DR rates suggests a factor of 2 or more uncertainty is inherent in the different theoretical techniques used to calculate DR for ions with partially filled valence shells (Arnaud & Raymond 1992; Savin et al. 1997, 1999). This is supported by laboratory measurements which have turned up errors of factors of 2 to orders of magnitude in calculated DR rates (Linkemann et al. 1995; Savin et al. 1997, 1999). The measurements also demonstrate that it is not possible a priori to know which set of calculations, if any, will agree with experiment. Taken all together, these results suggest that, for ions with partially filled valence shells, a factor of 2 uncertainty exists in almost all theoretical DR rates currently used for modeling photoionized plasmas.

As an example, we show in fig. 1 the published theoretical rates for DR onto C IV. Consisting of one electron outside of a closed shell, C IV is one of the simplest ions to treat theoretically and there have been numerous DR calculations, but theory has yet to converge. There is still a factor of ~ 2 spread between the different calculations over the entire temperature range.

Laboratory measurements are needed to determine the true DR rates and the best theoretical techniques for calculating DR. But as demonstrated by Savin et al. (1999), it is not possible to distinguish between different theoretical techniques based solely on the comparison of rate coefficients with experiments. The only unambiguous way to benchmark DR theory is through a detailed comparison of resonance strengths and energies.

N V, O VI, and Si IV are similar to C IV in that they consist of one electron outside of a closed shell. Based on our experimental studies and theoretical comparisons, we estimate a factor of 2 uncertainty in the calculated rates for DR onto N V, O VI, and Si IV. DR onto C IV has recently been measured by Mannervik et al. (1998) and Schippers (1999) and his collaborators. These groups are working to generate new C IV DR rates.

3. Model

Hellsten et al. (1998) have carried out hydrodynamic cosmological simulations for a redshift of $z = 3$. They present the resulting relationships for electron temperature $T_{\rm e}$ versus total hydrogen density $n_{\rm H}$ and for $n_{\rm H}$ versus H I column density $N_{\rm HI}$. We use their results, along with CLOUDY version 90.05, to investigate the effects of the uncertainty in the C IV, N V, O VI, and Si IV DR rates on the predicted IGM column densities for these ions. The temperature-density relation depends partly on the ionization structure of the gas and hence on the DR rates used. To simulate the possible effects the DR uncertainities have on this relation, we have also carried out calculations with $T_{\rm e}$ increased and decreased by a factor of 2. This does not significantly affect the conclusions in this paper.

We use the same spectral shape for the metagalactic radiation field as Hellsten et al. (1998) but have varied the decrement at the He II absorption edge (4 Ryd) by factors of 1, 2, 10, and 100. We assume that the decrement at the 4 Ryd does not affect the temperature-density relationship. This assumption is not strictly valid. Hui & Gnedin (1997) have shown that a decrement of 10^4 (twice our maximum decrement) does decrease the temperature, but by less than a factor of 2. Our modeling shows this uncertainty in the temperature-density relationship does not significantly affect the conclusions in this paper.

We use a flux at 912 Å of $J_\nu = 10^{-21}$ erg cm^{-2} s^{-1} sr^{-1} Hz^{-1}. For a metallicity, we use $[{\rm Z/H}] \equiv \log(n_Z/n_H) - \log(n_Z/n_H)_\odot = -2$. At $N_{\rm H} \gtrsim 10^{17}$ cm^{-2}, the IGM begins to become optically thick and self-shielding of the UV radiation needs to be taken into account (Rauch, Haehnelt, & Steinmetz 1997). Here we restrict our calculations to $N_{\rm H} \leq 10^{17}$ cm^{-2}.

4. Simulations and Astrophysical Implications

To simulate the effects of the uncertainties in the DR rates, we have run CLOUDY with the rates onto N V, O VI, and Si IV decreased by a factor of 2, unchanged, and increased by a factor of 2. Figures 2 to 4 show the resulting $N_{\rm NV}$, $N_{\rm OVI}$, and $N_{\rm SiIV}$ versus $N_{\rm HI}$. The resulting column densities differ from the column densities predicted using the unchanged DR rates by factors of up to ~ 1.9 for N V and Si IV and ~ 1.6 for O VI. This translates into a factor of up to $\sim 1.6 - 1.9$ uncertainty in any derived abundances.

For C IV, CLOUDY uses the low temperature DR rates of Nussbaumer & Storey (1983) and the high temperature DR rates of Shull & van Steenberg (1982). These rates lie at the lower end of the range of published C IV DR rates. We use the C IV DR rates unchanged and also increased by a factor of 2. Figure 5 shows the resulting $N_{\rm CIV}$ versus $N_{\rm HI}$. The predicted column density can be as much as a factor of ~ 1.7 smaller than that predicted using the unchanged DR rates. This could increase any inferred abundances by up to a factor of 1.7.

In Fig. 6 we have plotted the predicted $N_{\rm SiIV}/N_{\rm CIV}$ ratio versus $N_{\rm HI}$. Here we vary the SI IV and C IV DR rates. The resulting ratio could be up to 1.9 times smaller or 3.1 times larger than the ratio predicted using the unchanged DR rates. Hence, the inferred Si/C abundance ratio could be up to 3.1 times smaller or 1.9 times larger than that inferred using the unchanged DR rates.

The inferred Si/C ratio for the IGM is used to constrain the IMF of the earliest generation of stars. Giroux & Shull (1997) inferred a relative abundance ratio for the IGM of Si/C $\sim 2({\rm Si/C})_\odot$. Results such as those shown in fig. 6 indicate that uncertainties in the DR rates can either make Si/C $< ({\rm Si/C})_\odot$ or $> 3({\rm Si/C})_\odot$. However, Woolsey & Weaver (1995) have shown that, even if massive stars dominate the IMF, chemical evolution models with Si/C$> 3({\rm Si/C})_\odot$ are unrealistic. Abundance ratios this large would thus suggest that the metagalactic radiation field is not purely due to AGN but includes a significant component from stellar radiation (Giroux & Shull 1997).

In Fig. 7 we have plotted the predicted $N_{\rm SiIV}/N_{\rm CIV}$ versus $N_{\rm CII}/N_{\rm CIV}$. Comparisons between the observed ratios and model predictions are often used to constrain the magnitude of the decrement in the radiation field at 4 Ryd. The magnitude of the decrement affects the amount of He II photoionization heating of the IGM. Accurately determining this decrement has a direct bearing on the issue of late He II reionization, which could significantly affect the temperature-density relation of the IGM, and hence the interpretation of Ly-α forest observations (Miralda-Escudé 1994; Hui & Gnedin 1997). Many of the measured ratios fall in the range of $10^{-2} \lesssim {\rm N(CII)/N(CIV)} \lesssim 10^0$ (Songaila & Cowie 1996; Boksenberg 1989; Songaila 1998). Our models demonstrate that in this range the variation in the predicted $N_{\rm SiIV}/N_{\rm CIV}$ ratio due to a factor of 2 uncertainty in the DR rates can be as large as that due to a factor of 10 change in the decrement.

5. Conclusions

We have shown the effects on IGM models due to the estimated uncertainties in the DR rates. These uncertainties limit our ability to constrain the chemical abundances and the shape of the metagalactic radiation field at high redshift. Measurements of the relevant DR resonance strengths and energies are the only unambiguous way to remove these atomic physics uncertainties.

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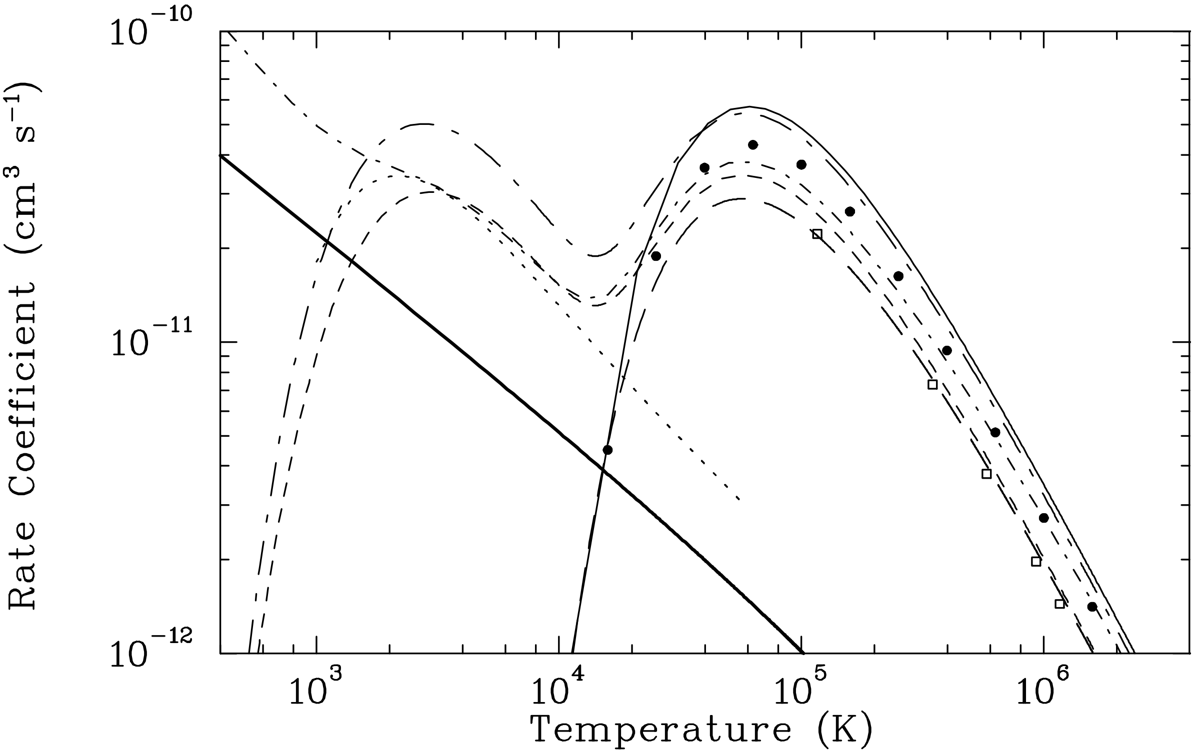

Fig. 1.— Published theoretical C IV to C III DR rates versus electron temperature. Calculations are from Burgess (1965, thin solid line), Shull & van Steenberg (1982, long-dashed curve); Nussbaumer & Storey (1983, short-dashed curve); McLaughlin & Hahn (1983, medium-dashed curve); Romanik (1988, dotted-long-dashed curve); Badnell (1989, filled circles); Chen (1991, open squares); and Nahar & Pradhan, who calculated a combined radiative recombination (RR) and DR rate, (1997, dotted-medium-dashed curve). The thick solid curve is the RR rate from Péquignot, Petitjean, & Boisson (1991).

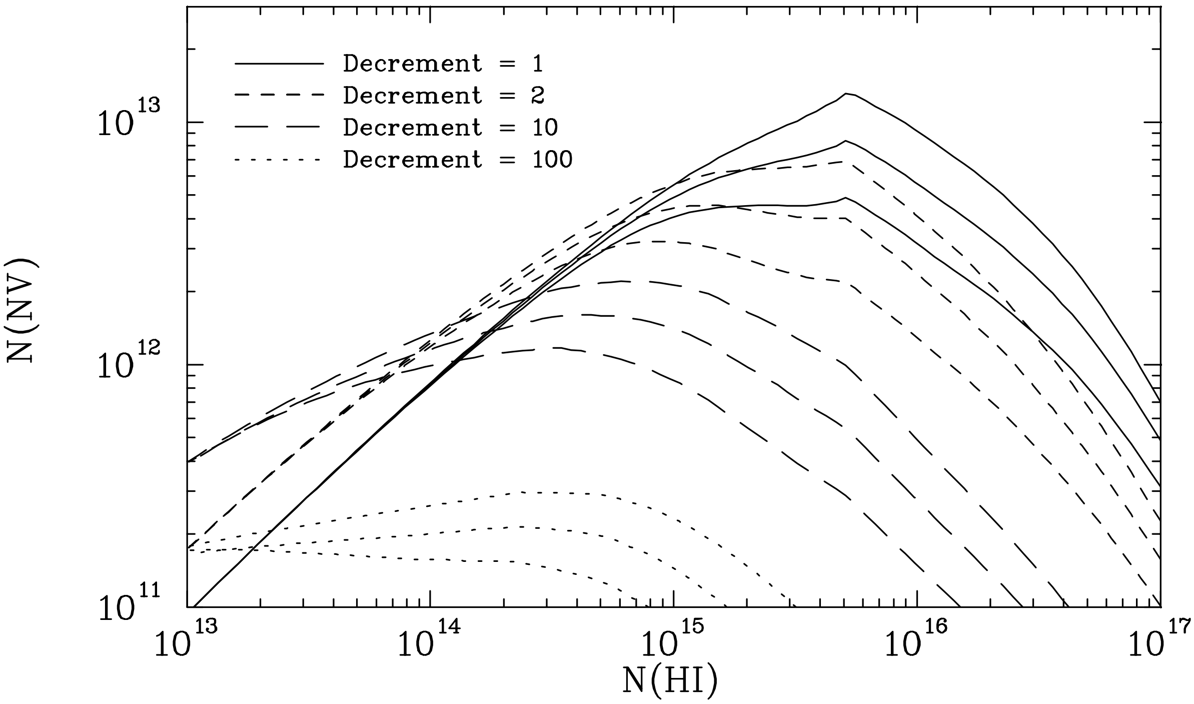

Fig. 2.— Predicted N V column density versus H I column density for the model described in Sec. 3. Each set of three curves represent a metagalactic radiation field with a decrement at 4 Ryd of 1 (solid curves), 2 (short-dashed curves), 10 (long-dashed curves), and 100 (dotted curves). We have also varied the the N V to N IV DR rate and left the other rates unchanged. For each set of three curves, the result are shown with the rate decreased by a factor of 2 (upper curve), unchanged (middle curve), and increased by a factor of 2 (lower curve).

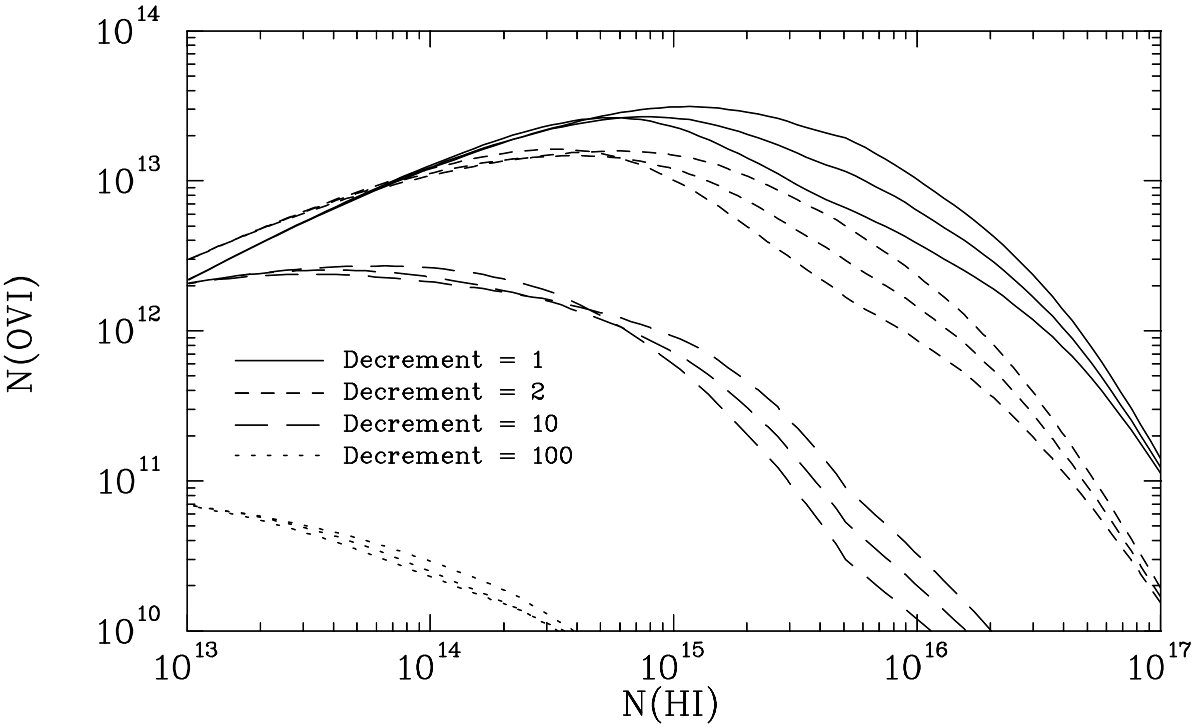

Fig. 3.— Predicted O VI column density versus H I column density. We have varied the the O VI to O V DR rate and left the other rates unchanged. See Fig. 2 for further details.

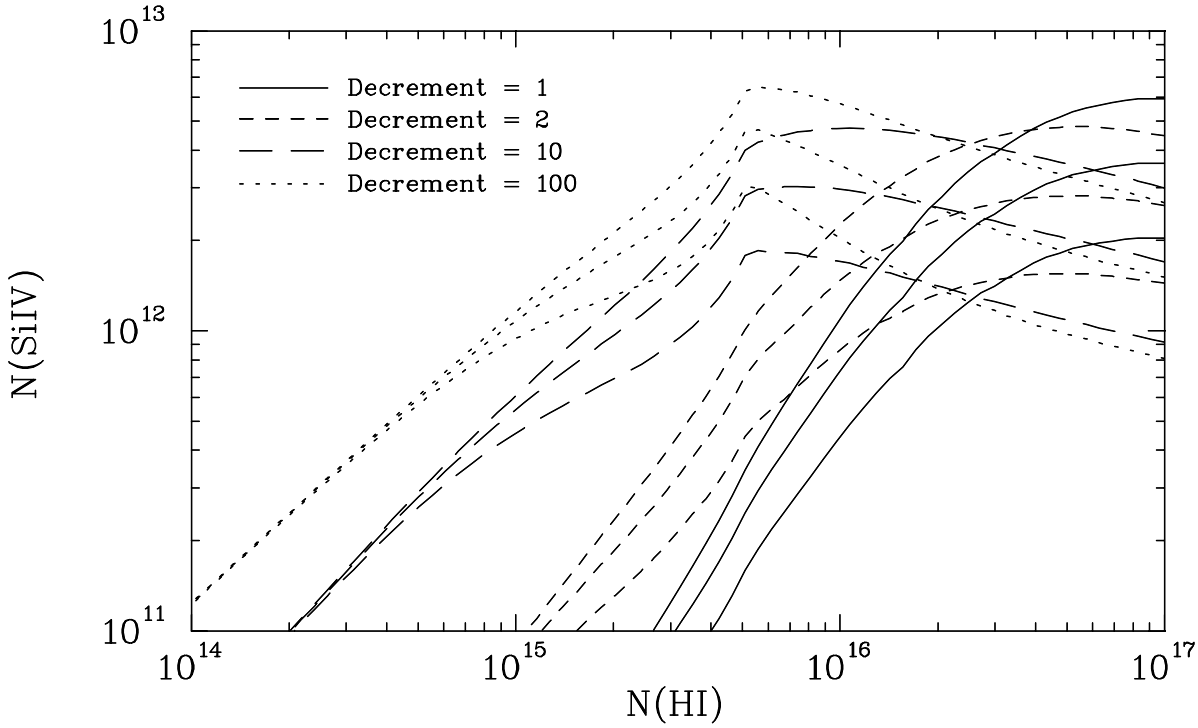

Fig. 4.— Predicted Si IV column density versus H I column density. We have varied the the Si IV to Si III DR rate and left the other rates unchanged. See Fig. 2 for further details.

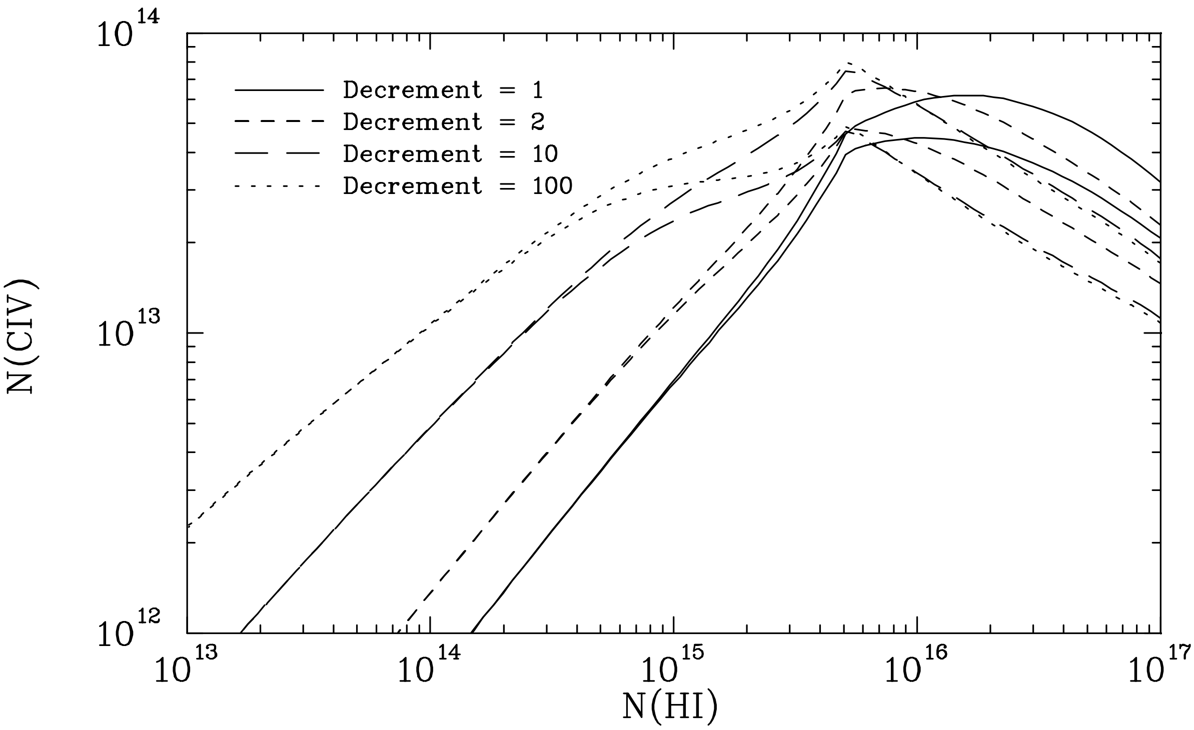

Fig. 5.— Predicted C IV column density versus H I column density. We have varied the the C IV to C III DR rate and left the other rates unchanged. For each set of curves, the results are shown for the rate unchanged (upper curve) and increased by a factor of 2 (lower curve). See Fig. 2 for further details.

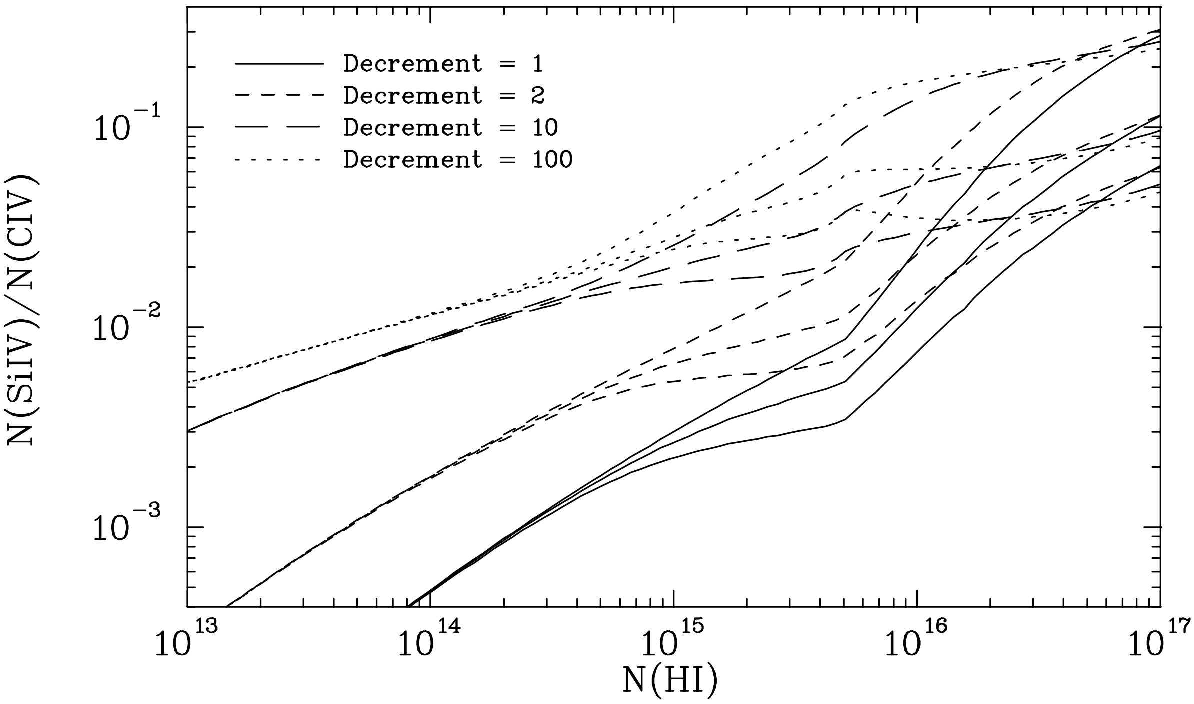

Fig. 6.— Predicted Si IV to C IV column densities versus H I column density. We have varied the C IV and Si IV DR rates and left the other rates unchanged. For each set of three curves, we have decreased the Si IV rate by a factor of 2 and increased the C IV rate by a factor of 2 (upper curve), left both rates unchanged (middle curve), and increased the Si IV rate by a factor of 2 while leaving the C IV rate unchanged (lower curve). See Fig. 2 for further details.

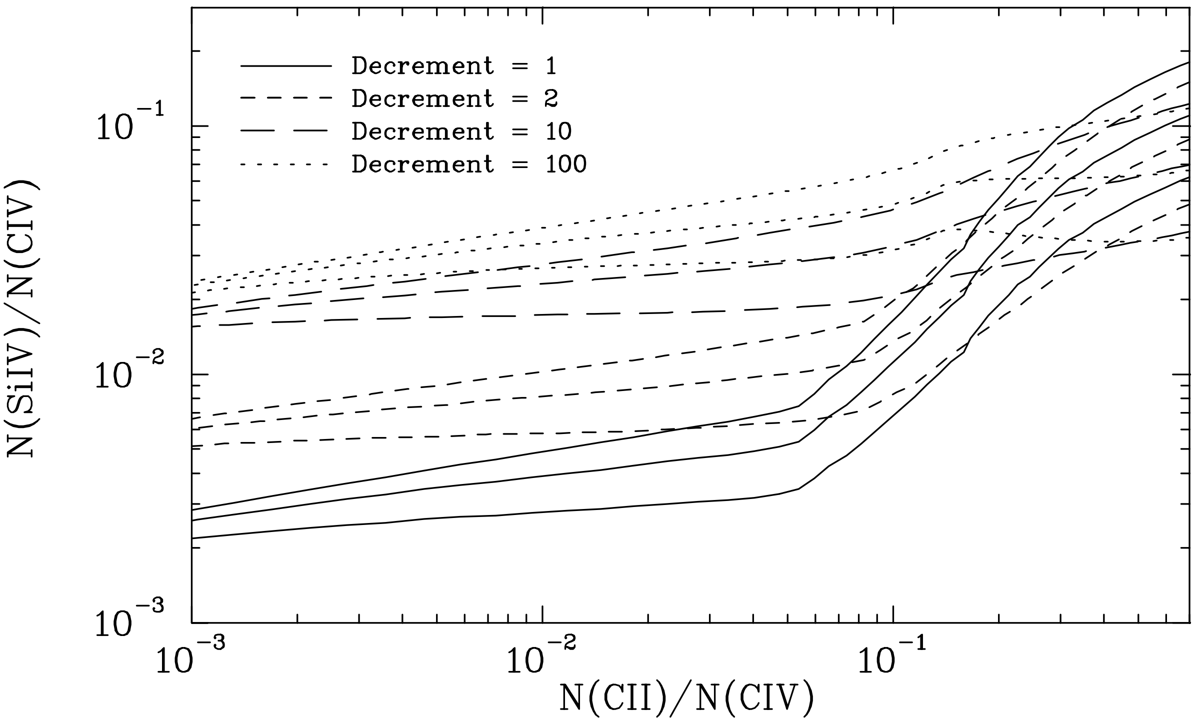

Fig. 7.— Ratio of Si IV to C IV column densities versus C II to C IV column densities. We have varied the the Si IV to Si III DR rate and left the other rates unchanged. See Fig. 2 for further details.